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A comparative overview of large-scale battery systems for electricity storage

Andreas Poullikkas *,[1]

Electricity Authority of Cyprus, P.O. Box 24506, 1399 Nicosia, Cyprus

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ABSTRACT

In this work, an overview of the different types of batteries used for large-scale electricity storage is carried out. In particular, the current operational large-scale battery energy storage systems around the world with their applications are identified and a comparison between the different types of batteries, as well as with other types of large-scale energy storage systems, is presented. The analysis has shown that the largest battery energy storage systems use sodium–sulfur batteries, whereas the flow batteries and especially the vanadium redox flow batteries are used for smaller battery energy storage systems. The battery electricity storage systems are mainly used as ancillary services or for supporting the large scale solar and wind integration in the existing power system, by providing grid stabilization, frequency regulation and wind and solar energy smoothing.

Contents

1. Introduction

Balancing power supply and demand is always a complex process. When large amounts of renewable energy sources (RES), such as photovoltaic (PV), wind and tidal energy, which can change abruptly with weather conditions, are integrated into the grid, this balancing process becomes even more difficult [1–3]. Effective energy storage can match total generation to total load precisely on a second by second basis. It can load-follow, adjusting to changes in wind and PV input over short or long time spans, as well as compensating for long-term changes [4]. While conventional power generation plants may take several minutes or even hours to come online and will consume fuel even on spinning reserve standby, storing renewable energy for later use effectively produces no emissions. Some well established technologies offer significant energy storage capacity but require specific geographical features

* Fax: +357 22 201809.
E-mail addresses: mspoul@ucy.ac.cy, apoullikkas@aus.edu

[1] Parts of this work were undertaken while the author was a Visiting Professor in the Department of Mechanical Engineering, College of Engineering, American University of Sharjah, PO Box 26666, Sharjah, United Arab Emirates.

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and considerable infrastructure. Others can be deployed rapidly to whenever they are required, but currently offer restricted capacity, often at high cost [20].

Although, due to their cost, batteries traditionally have not widely been used for large scale energy storage, they are now used for energy and power applications [6]. Energy applications involve the storage system discharge over periods of hours (typically one discharge cycle per day) with correspondingly long charging periods [7]. Power applications involve comparatively short periods of discharge (seconds to minutes), short recharging periods and often require many cycles per day. Secondary batteries, such as lead–acid and lithium-ion batteries can be deployed for energy storage, but require some re-engineering for grid applications [8].

Grid stabilization, or grid support, energy storage systems currently consist of large installations of lead–acid batteries as the standard technology [9]. The primary function of grid support is to provide spinning reserve in the event of power plant or transmission line equipment failure, that is, excess capacity to provide power as other power plants are brought online, especially in the case of isolated power systems [10]. These systems can take energy from the grid when either the frequency or voltage is too high and return that energy to the grid when the frequency or voltage begins to sag [11]. The current implementation can provide a few minutes of energy, but overall grid management, including shifting peak loads, and supporting RES, will require longer durations of storage and therefore re-engineering of storage systems to handle greater energy to power ratios [12].

In this work, a comparative overview of the different types of batteries used for large-scale electricity storage is carried out. In particular, the current operational large-scale battery energy storage systems around the world with their applications are identified and a comparison between the different types of batteries, as well as with other types of large-scale energy storage systems, is presented.

In Section 2, the different types of batteries used for large scale energy storage are discussed. Section 3 concerns the current operational large scale battery energy storage systems around the world, whereas the comparison of the technical features between the different types of batteries as well as with other types of large scale energy storage systems is presented in Section 4. A comparison of economic and environmental features of the large scale energy storage systems is discussed in Section 5. Finally, the conclusions are summarized in Section 6.

2. Large scale battery energy storage systems

Several types of batteries are used for large scale energy storage [13,14]. All consist of electrochemical cells, though no single cell type is suitable for all applications [15,16]. In this section, the characteristics of the various types of batteries used for large scale energy storage, such as the lead–acid, lithium-ion, nickel–cadmium, sodium–sulfur and flow batteries, as well as their applications, are discussed.

2.1. Lead–acid batteries

Lead–acid batteries, invented in 1859, are the oldest type of rechargeable battery and they use a liquid electrolyte, as illustrated in Fig. 1. The technology of lead–acid batteries is uncomplicated and manufacturing costs are low; however, such batteries are slow to charge, cannot be fully discharged and have a limited number of charge/discharge cycles, due to their low energy-to-weight ratio and their low energy-to-volume ratio [17]. The lead and sulfuric acid used are also highly toxic and create environmental hazards, which can be particularly ironic when used to accompany clean sources of power such as PV systems [5].

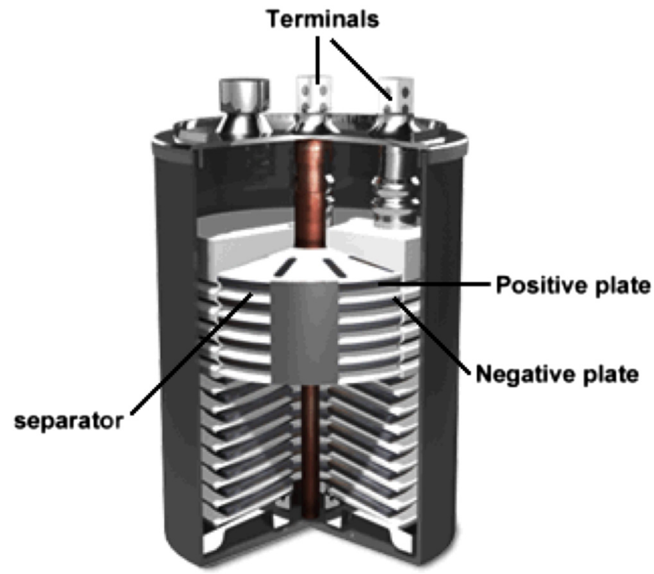


Fig. 1. Structure of lead–acid battery [88].

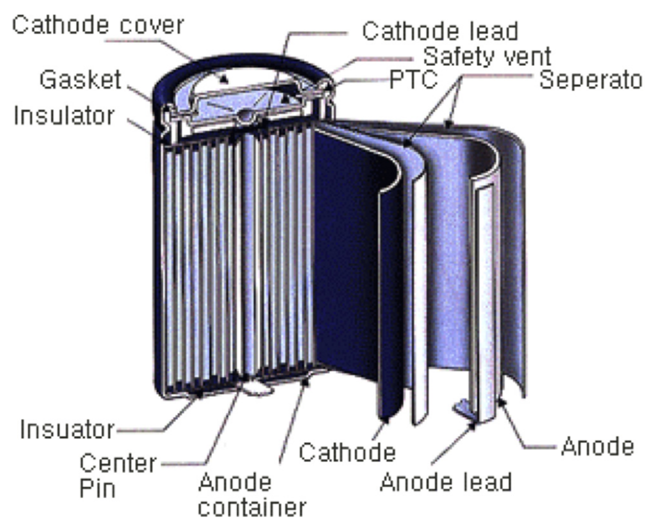


Fig. 2. Structure of lithium-ion battery [89]

The lead–acid battery chemistry can be modified for grid storage applications beyond stabilization applications by modification of the electrode structures. Lead–carbon electrodes are designed to combine high energy density of a well designed battery with the high specific power obtained via charging and discharging of the electrochemical double layer. Lead–carbon electrode research has been focused on the extension of cycle life durability and specific power [18]. Carbon is added to the negative electrodes, and while the carbon does not change the nature of the charge transfer reactions, it increases specific power and reduces the incidence of sulfation during charging cycles, which is one of the principal failure modes of traditional lead–acid batteries [19]. In these applications, it is required to have relatively deep discharges with good cycle life. With new carbon enhanced negative electrodes in valve regulated lead–acid (VRLA) batteries, the cycle life is improved up to a factor of 10 at significant rates [12].

In RES applications multiple deep-cycle lead–acid (DCLA) batteries, which provide a steady current over a long time period,

are connected together to form a battery bank. Indeed, banks of up to 1 MW of lead–acid batteries are already being used to stabilize wind farm power generation. For instance, DCLA are designed for backup and peak shifting in off-grid and grid-tied PV systems [20].

2.2. Lithium-ion batteries

Lithium-ion batteries, illustrated in Fig. 2, which have achieved significant penetration into the portable consumer electronics markets and are making the transition into hybrid and electric vehicle applications, have opportunities in grid storage as well [21–23]. If the industry′s growth in the vehicles and consumer electronics markets can yield improvements and manufacturing economies of scale, they will likely find their way into grid storage applications too [24,25]. Developers are seeking to lower maintenance and operating costs, deliver high efficiency, and ensure that large banks of batteries can be controlled [26]. Continued cost reduction, lifetime and state-of-charge improvements, will be critical for this battery chemistry to expand into these grid applications [12]. There are three types of lithium-ion batteries in commercial use, such as, cobalt, manganese and phosphate [27,28]. When lithium-ion batteries are used for utility-scale applications, it is to perform regulation and power management services and will be used for minutes of runtime [5,29,30].

2.3. Nickel–cadmium batteries

A nickel–cadmium battery is made up of a positive electrode with nickel oxyhydroxide as the active material and a negative electrode composed of metallic cadmium [31]. These are separated by a nylon divider. The electrolyte, which undergoes no significant changes during operation, is aqueous potassium hydroxide. During discharge, the nickel oxyhydroxide combines with water and produces nickel hydroxide and a hydroxide ion. Cadmium hydroxide is produced at the negative electrode [32]. To charge the battery the process can be reversed. However, during charging, oxygen can be produced at the positive electrode and hydrogen can be produced at the negative electrode. As a result some venting and water addition is required, but much less than required for a lead–acid battery.

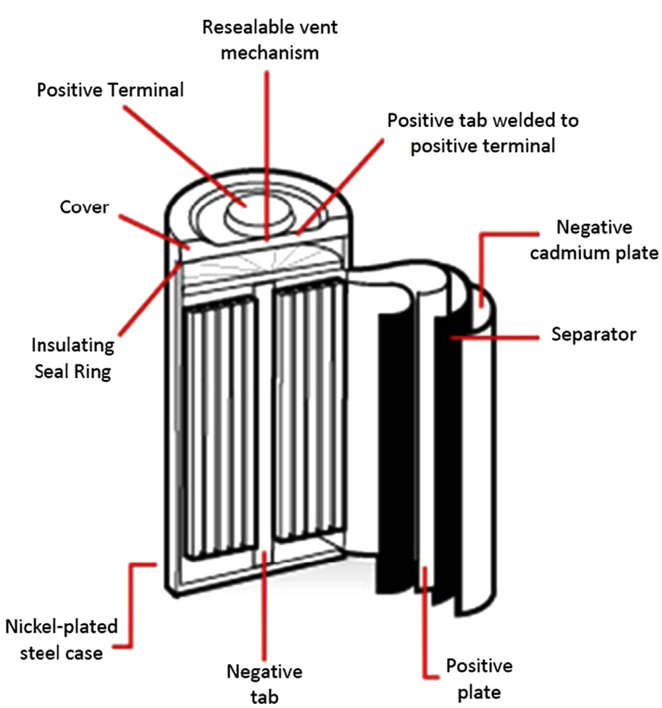


Fig. 3. Structure of sealed nickel–cadmium battery [36].

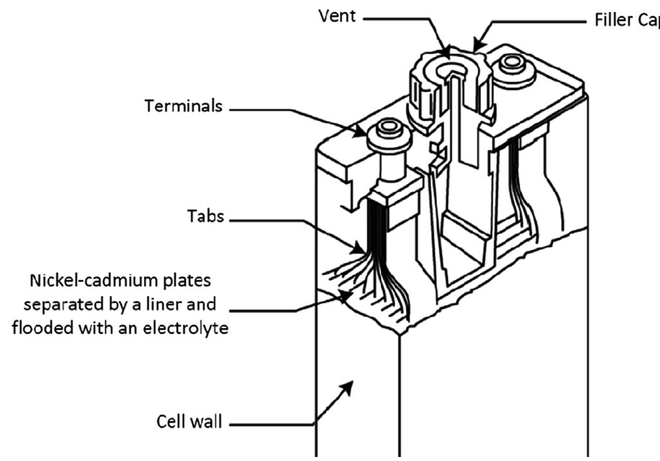


Fig. 4. Structure of vented nickel–cadmium battery [36].

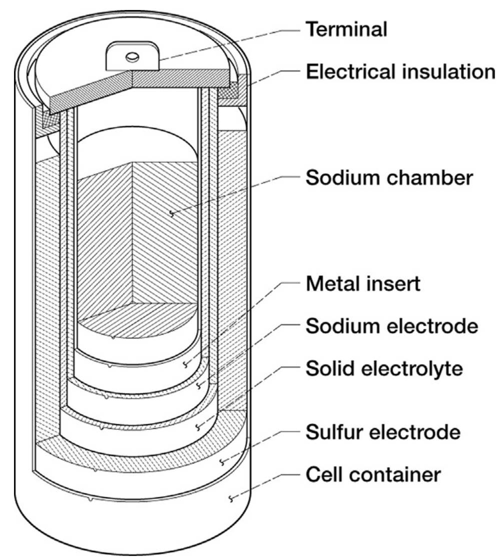


Fig. 5. Structure of sodium–sulfur battery [63].

There are two nickel–cadmium battery designs, the sealed, which is shown in Fig. 3 and the vented, which is shown in Fig. 4. Sealed nickel–cadmium batteries are the common, everyday rechargeable batteries used in a remote controls, lamps, etc. No gases are released from these batteries, unless a fault occurs [33]. Vented nickel–cadmium batteries have the same operating principles as sealed ones, but gas is released if overcharging or rapid discharging occurs. The oxygen and hydrogen are released through a low pressure release valve making the battery safer, lighter, more economical, and more robust than sealed nickel–cadmium batteries [34].

Sealed nickel–cadmium batteries are used commonly in commercial electronic products such as a remote control, where light weight, portability, and rechargeable power are important. Vented nickel–cadmium batteries are used in aircraft and diesel engine starters, where large energy per weight and volume are critical [35]. Nickel–cadmium batteries are ideal for protecting power quality against voltage sags and providing standby power in harsh conditions [37]. Recently, nickel–cadmium batteries have become popular as storage for solar generation because they can withstand high temperatures. However, they do not perform well during peak shaving applications, and consequently are generally avoided for energy management systems [36].

2.4. Sodium–sulfur batteries

Sodium–sulfur batteries are rechargeable high temperature battery technologies that utilize metallic sodium and offer attractive solutions for many large scale electric utility energy storage applications. Applications include load leveling, power quality and peak shaving, as well as renewable energy management and integration. A sodium–sulfur battery is a type of molten metal battery constructed from sodium and sulfur, as illustrated in Fig. 5. This type of battery has a high energy density, high efficiency of charge/discharge (75–86%), long cycle life, and is fabricated from inexpensive materials [38]. However, because of the operating temperatures of 300–350 °C and the highly corrosive nature of the sodium polysulfide discharge products, such cells are primarily suitable for large-scale, non-mobile applications such as grid energy storage [39].

Sodium β″-Alumina (beta double-prime alumina) is a fast ion conductor material and is used as a separator in several types of molten salt electrochemical cells. The primary disadvantage is the requirement for thermal management, which is necessary to maintain the ceramic separator and cell seal integrity. In the mid-1980s, the development of the sodium/metal-chloride system was launched. This technology offered potentially easier solutions to some of the development issues that sodium/sulfur was experiencing at the time [40]. Sodium/metal chloride cells, referred to as ZEBRA cells (ZEolite Battery Research Africa), also operate at relatively high temperatures, use a negative electrode composed of liquid sodium, and use a ceramic electrolyte to separate this electrode from the positive electrode. In these respects, they are similar to sodium/sulfur cells [41]. However, sodium/metal chloride cells include a secondary electrolyte of molten sodium tetrachloroaluminate ($NaAlCl_4$) in the positive electrode section, and an insoluble transition metal chloride ($FeCl_2$ or $NiCl_2$) or a mix of such chlorides, as the positive electrode. The advantages are that the cells have a higher voltage, wider operating temperature range, are less corrosive and have safer reaction products.

From the time of their invention through the mid-1990s, these two technologies were among the leading candidates believed to be capable of satisfying the needs of a number of emerging battery energy storage applications. Utility-scale sodium–sulfur batteries are manufactured by only one company, NGK Insulators Limited (Nagoya, Japan), which currently has an annual production capacity of 90 MW [12].

2.5. Flow batteries

A flow battery is a form of rechargeable battery in which electrolyte containing one or more dissolved electro-active species flows through an electrochemical cell that converts chemical energy directly to electricity. Additional electrolyte is stored externally, generally in tanks, and is usually pumped through the cell (or cells) of the reactor, although gravity feed systems are also available [42]. Flow batteries can be rapidly recharged by replacing the electrolyte liquid (in a similar way to refilling fuel tanks for internal combustion engines) while simultaneously recovering the spent material that would be recharged in a separate step [12].

Various classes of flow batteries exist including the redox (reduction–oxidation) flow battery, a reversible fuel cell in which all electro-active components are dissolved in the electrolyte [43]. If one or more electro-active components are deposited as a solid layer, the system is known as a hybrid flow battery, that is, the electrochemical cell contains one battery electrode and one fuel cell electrode. The main difference between these two types of flow batteries is that the energy of the redox flow battery, as with other fuel cells, is fully decoupled from the power, because the energy is related to the electrolyte volume, i.e., to the tank size, and the power to the electrode area, i.e., to the reactor size [44]. The hybrid flow battery, similar to typical batteries, is limited in energy by the size of the battery electrode, i.e. to the reactor size [45].

Energy producing electrochemical cells are generally divided into two categories. Cells that can be discharged only, with irreversible electrochemical reactions, are termed primary cells, while rechargeable cells with reversible reactions are termed secondary cells. Using this historical convention, a redox flow battery is better described as a secondary fuel cell or regenerative fuel cell, with the fundamental difference between batteries and fuel cells being whether energy is stored in a solid state electrode material (batteries) or in the electrolyte (fuel cells) [46]. This difference leads to the decoupling of energy and power in a fuel cell described above. Example of redox flow batteries is the vanadium redox flow battery, whereas for hybrid flow battery is the zinc–bromine battery [47].

Redox flow batteries, and to a lesser extent hybrid flow batteries, have the advantages of (a) flexible layout, due to separation of the power and energy components, (b) long cycle life, because there are no solid–solid phase changes, (c) quick response times, no need for equalization charging since the overcharging of a battery to ensure all cells have an equal charge, and

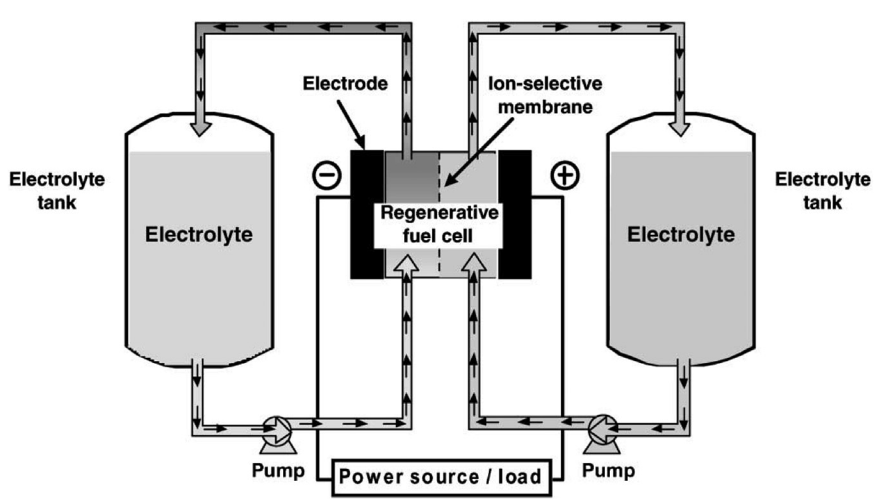


Fig. 6. Structure of vanadium redox battery [5]

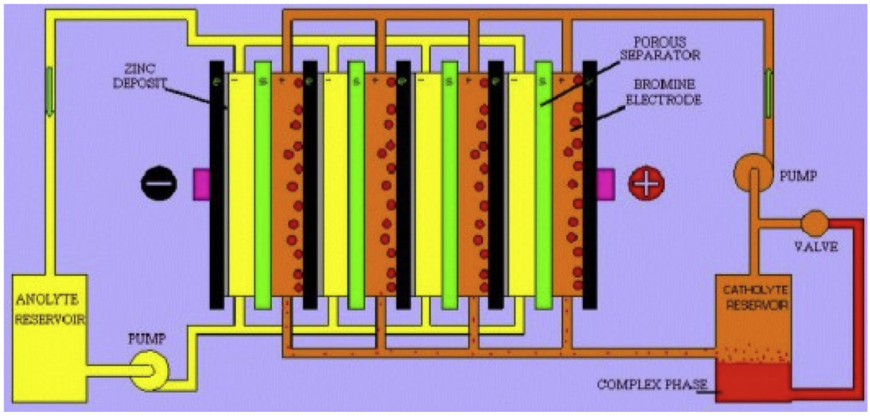


Fig. 7. Structure of zinc–bromine battery [90].

(d) no harmful emissions. Some types also offer easy state-of-charge determination, through voltage dependence on charge, low maintenance and tolerance to overcharge and/or overdischarge.

On the negative side, flow batteries are rather complicated in comparison with standard batteries as they may require pumps, sensors, control units and secondary containment vessels. The energy densities vary considerably but are, in general, rather low compared to portable batteries, such as the lithium-ion. Also, they have high initial self-discharge rate [48].

2.5.1. *Vanadium redox battery*

The vanadium redox battery is a type of rechargeable flow battery that employs vanadium ions in different oxidation states to store chemical potential energy, as illustrated in Fig. 6. The vanadium redox battery exploits the ability of vanadium to exist in solution in four different oxidation states, and uses this property to make a battery that has just one electro-active element instead of two [49,50]. The vanadium redox battery is a particularly clean technology, with high availability and a long life cycle. Its energy density is rather low, about 40 Wh/kg, though recent research indicates that a modified electrolyte solution produces a 70% improvement in energy density. Vanadium prices are volatile, though, with the increased demand for battery use likely to stress supply [20,51]. Efforts are focused on improved efficiency by reducing self-discharge losses and on lower cost electrode structures. Self-discharge is being addressed by only pumping electrolyte through the electrochemical stacks when necessary due to the magnitude of the load [12].

The main advantages of the vanadium redox battery are that it can offer almost unlimited capacity simply by using larger and larger storage tanks, it can be left completely discharged for long periods with no ill effects, it can be recharged simply by replacing the electrolyte if no power source is available to charge it, and if the electrolytes are accidentally mixed, the battery suffers no permanent damage [52,53]. The main disadvantages with vanadium redox technology are a relatively poor energy-to-volume ratio, and the system complexity in comparison with standard storage batteries [47].

The extremely large capacities possible from vanadium redox batteries make them well suited to use in large power storage applications such as helping to average out the production of highly variable generation sources such as wind or solar power, or to help generators cope with large surges in demand [54]. The limited self-discharge characteristics of vanadium redox batteries make them useful in applications where the batteries must be stored for long periods of time with little maintenance while maintaining a ready state. This has led to their adoption in some military electronics. Their extremely rapid response times also make them superbly well suited to UPS type applications, where they can be used to replace lead–acid batteries and even diesel generators [49].

2.5.2. *Zinc–bromine battery*

The zinc–bromine flow battery is a type of hybrid flow battery and is stored in two tanks, as illustrated in Fig. 7. When the battery is charged or discharged, the solutions (electrolytes) are pumped through a reactor stack and back into the tanks. One tank is used to store the electrolyte for the positive electrode reactions and the other for the negative [55]. Zinc–bromine batteries from different manufacturers have energy densities ranging from 34.4 to 54 Wh/kg. The predominantly aqueous electrolyte is composed of zinc bromide salt dissolved in water. During charge, metallic zinc is plated from the electrolyte solution onto the negative electrode surfaces in the cell stacks. Bromide is converted to bromine at the positive electrode surface of the cell stack and is immediately stored as a safe, chemically complex organic phase in the electrolyte tank. Each fully recyclable high-density polyethylene (HDPE) cell stack has up to 60 bipolar, plastic electrodes between a pair of anode and cathode end blocks [56].

The zinc–bromine battery can be regarded as an electroplating machine. During charging zinc is electroplated onto conductive electrodes, while at the same time bromine is formed. On discharge the reverse process occurs, the metallic zinc plated on the negative electrodes dissolves in the electrolyte and is available to be plated again at the next charge cycle. It can be left fully discharged indefinitely without damage [57]. The primary features of the zinc bromine battery are (a) high energy density relative to lead–acid batteries, (b) 100% depth of discharge capability on a daily basis, (c) high cycle life of more than 2000 cycles at 100% depth of discharge, at which point the battery can be serviced to increase cycle life to over 3500 cycles, (d) no shelf life limitations as zinc–bromine batteries are non-perishable, unlike lead–acid and lithium-ion batteries, (e) scalable capacities from 10 kWh to over 500 kWh systems and (f) the ability to store energy from any electricity generating source [58].

Three examples of zinc–bromine flow batteries are ZBB Energy Corporation's Zinc Energy Storage System (ZESS), RedFlow Limited's Zinc Bromine Module (ZBM), and Premium Power's Zinc-Flow Technology. These battery systems have the potential to provide energy storage solutions at a lower overall cost than other energy storage systems such as lead–acid, vanadium redox, sodium–sulfur, lithium-ion and others [59].

Table 1
Worldwide operational large scale battery systems.

Project	Location	System size		Battery type	Services	Application
		MWe	MWh			
Amplex Group	United Arab Emirates	350	N/A	Sodium–sulfur	Ancillary services	Grid stabilization, frequency regulation, voltage support, power quality, load shifting and energy arbitrage
Tokyo Electric Power Company	Japan	200	N/A	Sodium–sulfur	N/A	N/A
Other Japanese Electric Companies	Japan	60	N/A	Sodium–sulfur	N/A	N/A
Abu Dhabi Water and Electricity Authority	United Arab Emirates	48	N/A	Sodium–sulfur	N/A	N/A
Japan Wind Development Co.	Japan	34	238	Sodium–sulfur	Wind integration	N/A
Laurel Mountain	West Virginia, USA	32	8	Lithium-ion	Wind integration	Frequency regulation and wind energy smoothing
Golden Valley Electric Association	Alaska, USA	27	14.6	Nickel–Cadmium	Ancillary services	Spinning reserve and power system stabilization
Zhangbei	China	20	36	Lithium-ion	Solar and wind integration	Grid stabilization, increased reliability, wind and solar energy smoothing
AES Westcover coal fired power station	New York, USA	20	N/A	N/A	Ancillary services	Frequency regulation
AES Gener new power plant installation	Northern Chile	20	N/A	N/A	Ancillary services	N/A
Puerto Rico Electric Power Authority Battery System	Puerto Rico	20	14	Lead–acid	Ancillary services	Frequency control and spinning reserve
Kahuku-kahuku wind power project	Hawaii, USA	15	10	N/A	Wind integration	Ramp control and curtailment mitigation
Southern California Edison Chino Battery Storage Project	California, USA	14	40	Lead–acid	Ancillary services	Load leveling, transmission line stability, local VAR control and black start
AES Gener Los Andes substation	Chile	12	N/A	Lithium-ion	Ancillary services	Frequency regulation and spinning reserve
American Electric Power	West Virginia, USA	11	N/A	Sodium–sulfur	N/A	N/A
KWP II Kaheawa wind power II project	Hawaii, USA	10	20	N/A	Wind integration	Uninterruptible power service
Berliner Kraft und Licht Battery System	Germany	8.5	14	Lead–acid	Ancillary services	Frequency regulation and spinning reserve
Pacific Gas and Electric Company	California, USA	6	N/A	Sodium–sulfur	N/A	N/A
Sumitomo Densetsu Office Battery System	Japan	3	0.8	Vanadium redox flow	Ancillary services	Peak shaving
Project Sano	California, USA	2	N/A	N/A	Ancillary services	Frequency regulation
Project Carina	Indiana, USA	2	N/A	N/A	Ancillary services	Frequency regulation
Brockway Standard Lithography Plant	Georgia, USA	2	0.055	Lead–acid	Ancillary services	Power quality and uninterruptible power supply
Kauai Island utility Co-op	Hawaii, USA	1.5	1	N/A	Solar integration	Utility owned
Maui Kaheawa wind power project	Hawaii, USA	1.5	1	N/A	Wind integration	Ramp control and curtailment mitigation
Xcel solar technology acceleration center	Colorado, USA	1.5	1	N/A	Solar integration	Ramp control, curtailment mitigation and grid services
UPS system	Japan	1.5	N/A	Vanadium redox flow	Ancillary services	N/A
Hokkaidou Electric Power Company	Japan	1.5	N/A	Sodium–sulfur	N/A	N/A
Long Island, New York Bus Terminal Energy Storage System	New York, USA	1.2	6.5	Sodium–sulfur	Ancillary services	Load shifting
Lanai la Ola solar farm project	Hawaii, USA	1.125	0.5	N/A	Solar integration	Ramp control and grid services
Project Barbados	Pennsylvania, USA	1	N/A	N/A	Ancillary services	Frequency regulation
Project Redstone	Texas, USA	1	N/A	N/A	Ancillary services	Grid stabilization
New York Power Company	New York, USA	1	N/A	Sodium–sulfur	N/A	N/A
Xcel	Minnesota, USA	1	N/A	Sodium–sulfur	N/A	N/A
Younicos	Germany	1	N/A	Sodium–sulfur	N/A	N/A
Matlakatla Power and Light Battery System	Alaska, USA	1	1.4	Lead–acid	Ancillary services	Voltage regulation and displacing diesel generation
AEP Sodium Sulfur Distributed Energy Storage System	West Virginia, USA	1	7.2	Sodium–sulfur	Ancillary services	Substation upgrade deferral
EDF	France	1	N/A	Sodium––sulfur	N/A	N/A
Enercon	Germany	0.8	N/A	Sodium–sulfur	N/A	N/A
Ford Michigan assembly plant	Michigan, USA	0.75	2	N/A	End user	Peak shaving and load leveling
South Pole Telescope project	Antarctica	0.5	0.1	N/A	Ancillary services	Peak shaving and load leveling
Crescent Electric Membership Cooperative	North Carolina, USA	0.5	0.5	Lead–acid	Ancillary services	Peak shaving
Tomari Wind Hills of Hokkaido	Japan	0.275	N/A	Vanadium redox flow	Wind integration	Wind energy smoothing

Table 1 (*continued*)

Project	Location	System size		Battery type	Services	Application
		MWe	MWh			
Pacificorp Castle Valley Battery System	Utah, USA	0.25	2	Vanadium redox flow	Ancillary services	Distribution line upgrade deferral and voltage support
Huxley Hill Wind Farm	Tasmania	0.2	0.8	Vanadium redox flow	Wind integration	Wind energy smoothing
Southern California at Tehachapi	California, USA	N/A	32	Lithium-ion	Wind integration	Grid stabilization, decreased transmission losses, diminished congestion, increased reliability and wind energy smoothing
Smart grid integration demonstration with DTE Energy	Michigan, USA	N/A	0.25	N/A	Smart grid PV integration	Dispatchable PV integration

3. Operational and planned large scale battery energy systems

In this section, the operational and planned large scale battery energy systems around the world, which are tabulated in Tables 1 and 2, respectively, are discussed [12,60–63]. It is observed that the largest battery energy storage systems use sodium–sulfur batteries, whereas the flow batteries and especially the vanadium redox flow batteries are used for smaller battery energy storage systems. The battery energy storage systems are mainly used as ancillary services or for supporting the large scale solar and wind integration in the existing power system, by providing grid stabilization, frequency regulation and wind and solar energy smoothing [32,64–67].

Specifically, the Amplex Group has employed a battery energy storage system with sodium–sulfur batteries in the United Arab Emirates, with a capacity of 350 MWe, which is used as ancillary service for grid stabilization, frequency regulation, voltage support, power quality, load shifting and energy arbitrage [68]. Furthermore, in Laurel Mountain of West Virginia of USA, a battery energy storage system with lithium-ion batteries and a capacity of 32 MWe and 8 MWh has been employed, which is used for helping large scale wind integration in the existing power system by providing frequency regulation and wind energy smoothing [61].

The Golden Valley Electric Association has employed a battery energy storage system with nickel–cadmium batteries in Alaska of USA, with a capacity of 27 MWe and 14.6 MWh, which is used as ancillary service for spinning reserve and power system stabilization [69]. Moreover, the Puerto Rico Electric Power Authority has employed a battery energy storage system with lead–acid batteries in Puerto Rico, with a capacity of 20 MWe and 14 MWh, which is used as ancillary service for frequency control and spinning reserve [12]. Finally, The Sumitomo Densetsu Office has employed a battery energy storage system with vanadium redox flow batteries in Japan, with a capacity of 3 MWe and 0.8 MWh, which is used as ancillary service for peak shaving [67].

Regarding the planned large scale battery systems, the most important is the Rubenius battery energy system in California, USA, which will have a capacity of 1000 MWe and will require an area of 1,416,400 m^2, as shown in Fig. 8. The battery system that will be used is sodium–sulfur type and the system will be used for helping for large scale solar and wind integration in the existing power system, by providing grid stabilization, frequency regulation, voltage support, power quality, load shifting and energy arbitrage [71,68].

4. Comparison of technical features

In this section, a technical comparison between the different types of batteries, as well as with other types of large energy storage systems is carried out. In particular, the advantages and disadvantages of each energy storage system as well as their performance for power and energy applications [20,70] are tabulated in Table 3, whereas their technical characteristics [36] are tabulated in Table 4. It is observed that lithium-ion batteries and sodium–sulfur batteries have high power and energy densities and high efficiency, but they have high production costs. Also, pumped hydro energy storage systems and compressed air energy storage systems have high capacity, but they have special site requirements [72]. Furthermore, it is observed that with the exception of pumped hydro energy storage systems and compressed air energy storage systems, all the other energy storage systems are fully capable and suitable for providing power very quickly in the power system [73]. Regarding the energy applications, sodium–sulfur batteries, flow batteries, pumped hydro energy storage systems and compressed air energy storage systems are fully capable and suitable for providing energy very quickly in the

Table 2
Planned large scale battery systems in the world.

Project	Location	System size		Required area	Battery type	Services	Application
		MWe	MWh	(m^2)			
Rubenius	California, USA	1000	N/A	1,416,400	Sodium–sulfur	Solar and wind integration	Grid stabilization, frequency regulation, voltage support, power quality, load shifting and energy arbitrage
Long Island Power Authority	New York, USA	400	N/A	N/A	N/A	Ancillary services	Peak shaving
Power Sound Energy	Washington, USA	200	N/A	N/A	N/A	Ancillary services	Peak shaving
Tres Amigas	New Mexico, USA	100	200	N/A	N/A	Ancillary services	Peak shaving



Fig. 8. Under construction Rubenius 1 GWe battery energy system in California, USA [71].

power system, whereas the rest of the energy storage systems are feasible but not quite practical or economical [74].

In Table 5, the technical suitability of the large scale energy storage systems to different applications [36] is provided. It is observed that lead–acid and flow batteries are suitable for all applications. Pumped hydro energy storage systems and compressed air energy storage systems, are suitable for load levelling, peak generation, conventional spinning reserve, renewable integration and renewables back-up applications [70]. The compressed air energy storage systems are also suitable for emergency back-up applications. Finally, flywheels are suitable for transit and end-use ride-through, uninterruptible power supply, peak generation, fast response spinning reserve and renewable integration applications.

5. Comparison of economic features

In this section, a comparative economic comparison between the different types of batteries, as well as between other types of large energy storage systems is carried out. In particular, the power and energy related costs, as well as the environmental issues of each energy storage system [36,75–83] are tabulated in Table 6. It is observed that a range of values exists for each system regarding power and energy related costs, due to various capacity sizes of the operational large scale energy storage systems around the world. Specifically, lead–acid batteries, sodium–sulfur batteries, flywheels and compressed air energy storage systems, have the lowest range of values regarding power related costs [84]. Conversely, nickel–cadmium batteries, the two types of flow batteries, vanadium redox and zinc–bromine, as well as pumped hydro energy storage systems, have higher range of values regarding power related costs [85].

Regarding the energy related cost, pumped hydro and compressed air energy storage systems have the lowest range of values, followed by the lead–acid, sodium–sulfur, zinc–bromine flow batteries and flywheels [86,87]. The nickel–cadmium and vanadium redox flow batteries have the highest range of values regarding energy related costs. Regarding the environmental issues of each large scale energy storage system, the different types of batteries have to handle chemical disposal, specifically lead–acid and nickel–cadmium batteries which dispose lead and toxic cadmium. The effect of pumped hydro energy storage systems in the environment is the pollution during the construction of the two reservoirs, whereas for the compressed air energy storage systems are the emission of gas into atmosphere. Finally, flywheels have only a slight effect in the environment.

6. Conclusions

In this work, a comparative overview of the different types of batteries used for large scale energy storage was carried out. In particular, the current operational large scale battery energy storage systems around the world with their applications were identified and a comparison between the different types of batteries, as well as with other types of large scale energy storage systems, was presented. The analysis has shown that the largest battery energy storage systems use sodium–sulfur batteries, whereas the flow batteries and especially the vanadium redox flow batteries are used for smaller battery energy storage systems. The battery energy storage systems are mainly used as ancillary services or for supporting the large scale solar and wind integration in the existing power system, by providing grid stabilization, frequency regulation and wind and solar energy smoothing.

By comparing the different types of batteries, as well as other types of large scale energy storage systems, it was observed that lithium-ion batteries and sodium–sulfur batteries have high power and energy densities and high efficiency, but they have high production costs. Also, pumped hydro energy storage systems and compressed air energy storage systems have high capacity, but they have special site requirements. Furthermore, it was observed that with the exception of pumped hydro energy storage systems and compressed air energy storage systems, all the other energy storage systems are fully capable and suitable for providing power very quickly in the power system. Regarding the energy applications, sodium–sulfur batteries, flow batteries, pumped hydro energy storage systems and compressed air energy storage systems are fully capable and suitable for providing energy very quickly in the power system, whereas the rest of the energy storage systems are feasible but not quite practical or economical.

Table 3
Comparison of large scale energy storage systems.

Energy storage technology	Advantages	Disadvantages	Power applications	Energy applications
Lead–acid batteries	Low power density and capital cost	Limited life cycle when deeply discharged	Fully capable and suitable	Feasible but not quite practical or economical
Lithium-ion batteries	High power and energy densities, high efficiency	High production cost, requires special charging circuit	Fully capable and suitable	Feasible but not quite practical or economical
Sodium–sulfur batteries	High power and energy densities, high efficiency	Production cost, safety concerns (addressed in design)	Fully capable and suitable	Fully capable and suitable
Flow batteries	High energy density, independent power and energy ratings	Low capacity	Suitable for this application	Fully capable and suitable
Flywheels	High efficiency and power density	Low energy density	Fully capable and suitable	Feasible but not quite practical or economical
Pumped hydro-energy storage systems	High capacity	Special site requirement	Not feasible or economical	Fully capable and suitable
Compressed air energy storage systems	High capacity, low cost	Special site requirement, needs gas fuel	Not feasible or economical	Fully capable and suitable

Table 4
Technical characteristics of large scale energy storage systems.

Technology	Power rating (MW)	Discharge duration	Response time	Efficiency (%)	Lifetime
Lead–acid batteries	< 50	1 min–8 h	< 1/4 cycle	85	3–12 years
Nickel–cadmium batteries	< 50	1 min–8 h	N/A	60–70	15–20 years
Sodium–sulfur batteries	< 350	< 8 h	N/A	75–86	5 years
Vanadium redox flow batteries	< 3	< 10 h	N/A	70–85	10 years
Zinc–bromine flow batteries	< 1	< 4 h	< 1/4 cycle	75	2000 cycles
Flywheels	< 1.65	3–120 s	< 1 cycle	90	20 years
Pumped hydro energy storage systems	100–4000	4–12 h	s–min	70–85	30–50 years
Compressed air energy storage systems	100–300	6–20 h	s–min	64	30 years

Table 5
Technical suitability of large scale energy storage systems.

Storage application	Lead-acid batteries	Flow batteries	Flywheels	Pumped hydro energy storage systems	Compressed air energy storage systems
Transit and end-use ride-through	✓	✓	✓		
Uninterruptible power supply	✓	✓	✓		
Emergency back-up	✓	✓			✓
Transmission and distribution stabilization and regulation	✓	✓			
Load leveling[a]	✓	✓		✓	✓
Load following[b]	✓	✓			
Peak generation	✓	✓	✓	✓	✓
Fast response spinning reserve	✓	✓	✓		
Conventional spinning reserve	✓	✓	✓	✓	✓
Allow for renewable integration	✓	✓	✓	✓	✓
Suitable for renewables back-up	✓	✓		✓	✓

[a] Reducing the large fluctuations that occur in electricity demand.
[b] Adjusting power output as demand for electricity fluctuates throughout the day.

Table 6
Economical and environmental characteristics of large scale energy storage systems.

Technology	Capital cost (US$/kWh)	Environmental issues
Lead–acid batteries	50–310	Lead disposal
Nickel–cadmium batteries	400–2400	Toxic cadmium
Sodium–sulfur batteries	180–500	Chemical handling
Vanadium redox flow batteries	175–1000	Chemical handling
Zinc–bromine flow batteries	200–600	Chemical handling
Flywheels	400–800	Slight
Pumped hydro-energy storage systems	8–100	Reservoir
Compressed air energy storage systems	2–100	Gas emissions

Concerning the technical suitability of the large scale energy storage systems to different applications, it was observed that lead–acid and flow batteries are suitable for all applications. Pumped hydro energy storage systems and compressed air energy storage systems are suitable for load levelling, peak generation, conventional spinning reserve, renewable integration and renewables back-up applications. The compressed air energy storage systems are also suitable for emergency back-up applications. Flywheels are suitable for transit and end-use ride-through, uninterruptible power supply, peak generation, fast response spinning reserve and renewable integration applications.

Concerning the economic comparison of the large scale energy storage systems it was observed that a range of values exists for

each system regarding power and energy related costs, due to various capacity sizes of the operational large scale energy storage systems around the world. Specifically, lead–acid batteries, sodium–sulfur batteries, flywheels and compressed air energy storage systems, have the lowest range of values regarding power related costs. Conversely, nickel–cadmium batteries, the two types of flow batteries, vanadium redox and zinc–bromine, as well as pumped hydro energy storage systems, have higher range of values regarding power related costs.

Regarding the energy related cost, pumped hydro and compressed air energy storage systems have the lowest range of values, followed by the lead–acid, sodium–sulfur, zinc–bromine flow batteries and flywheels. The nickel–cadmium and vanadium redox flow batteries have the highest range of values regarding energy related costs. Regarding the environmental issues of each large scale energy storage system, the different types of batteries have to handle chemical disposal, specifically lead–acid and nickel–cadmium batteries which dispose lead and toxic cadmium. The effect of pumped hydro energy storage systems in the environment is the pollution of the construction of the two reservoirs, whereas for the compressed air energy storage systems is the emission of gas into atmosphere. Finally, flywheels have only a slight effect in the environment.

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